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Y a-t-il encore de la place en bas ?

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Introduction. Nanotechnoscience: The End of the Beginning

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Is there still room at the bottom? The question providing the theme for the present issue of *Philosophia Scientiæ* is, of course, adapted from Richard Feynman's well-known speech at the 1959 meeting of the American Physical Society. On this occasion he attracted physicists' attention to the vast potential of working at the scale of the nanometre if not the ångström, using the catchy title: "Plenty of Room at the Bottom" [Feynman 1959]. This hookline from a famous Nobel laureate physicist served as a motto for the emerging field of nanoscience and nanotechnology (which we will here abbreviate to nanoresearch) in the early 2000s.

Almost 20 years on, nanoresearch has become a well-established area of research and development in both the public and the private sectors with a large volume of publications, undergraduate and graduate programmes, international conferences, start-ups and commercial applications. It seems timely, therefore, to reflect on where nanoresearch has come from, where it is now and the orientation for its development over the coming decades. The purpose of this issue is not to assess what has been achieved in nanoresearch in terms of breakthrough discoveries or return on research investment. Rather, the aim is to look back and consider whether nanoresearch changed the landscape of academic research and what kinds of reconfiguration of research practice it has brought about. More generally, what lessons can the philosophy of science learn from the form and development of nanoresearch?

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With this project in mind, we launched a call for papers aimed principally at philosophers to address questions such as: what are the relationships between science and technology in nanoresearch? What is the impact of nanoresearch on traditional disciplines, notably in terms of the much-vaunted NBIC (Nanotechnology, Biology and medicine, Information sciences, and Cognitive Sciences) convergence hypothesis? We also invited researchers who have been active in the field since the early days of nanoresearch to present their own views in a short commentary format. These more personal texts are extremely valuable as they bring to light interesting critical issues in the field (both concrete and theoretical) in a lively and engaging manner.

1 Drexler's Feynman: A founder myth for nanoresearch

Feynman's futuristic visions of miniaturised machines and information systems were communicated to a wider general public by K. Eric Drexler, the self-appointed prophet of the coming nanotechnological revolution, in his successful 1986 book *Engines of Creation* [Drexler 1986]. In his energetic campaign for a nanotechnology revolution, Drexler featured Feynman as the founding father of the nanotechnology era [Drexler 2004]. The Foresight Institute, a non-profit organization founded by Drexler's disciples, even funds a Feynman Prize which has been awarded every year since 1997.

This celebration of a charismatic physicist as the founder of a new scientific field, if not a new scientific era is a quite typical instantiation of the phenomenon of the invention of precursors, familiar to historians of science. This being said, associating Feynman's name with the emergence of nanoresearch is certainly justified, since Feynman clearly did envision new opportunities for design at the atomic level. The miniaturisation of materials, machines and computing systems, Feynman argued, could be pursued all the way down to the displacement and rearrangement of individual atoms. In particular, information storage could be inspired by the "biological example of writing information on a small scale" seen in the molecule of DNA.[1] Feynman pointed out that this new kind of design would require more powerful microscopes, which would allow physicists to cooperate with chemists in the synthesis of materials and molecules. He also insisted on the fact that atoms have specific behaviours guided by specific forces, and argued that these characteristics could provide new opportunities for design.

For us, there is a striking resonance between Feynman's predictions and today's nanoresearch, but we can safely assume that Feynman's colleagues. . . ..

1. The famous paper on the double-helix structure of DNA—"The molecular structure of nucleic acids"—was published by Francis Crick and James Watson in 1953.

did not interpret his speculations about the future in the same way as we do. In the context of the Cold War, Feynman did not really need to draw his colleagues' attention to atoms and their properties since a significant number of them were working in atomic physics. What might well have come across to them in the phrase "room at the bottom" is an alternative message like: "Hey guys! Instead of splitting atoms to make bombs or nuclear reactors, why not try using them to build something?" Feynman was suggesting a new alternative route for leaving the "military-industrial complex", and this option seems to have attracted the attention of the physics community for about three years. But because most research infrastructure continued to be oriented towards nuclear physics, the perspectives for research outlined in "Room at the bottom" failed to engage physicists' interest over a longer period. Drexler's reading of Feynman's vision of the future proceeds from its decontextualization and recontextualization against the background of the emergence of new techniques of microscopy. As Feynman had rightly pointed out, microscopy turned out to be a critical factor for working effectively at the level of atoms and molecules, since it was the construction of the Scanning Tunelling Microscope (STM) by two IBM researchers in 1981 and its rapid appropriation by academic scientists that triggered the take-off of nanotechnology [Mody 2004*a*,*b*]. The possibilities of near-field microscopy were reinforced by the development of the Atomic Force Microscope (AFM), another crucial contribution to the take-off of nanoresearch.

In addition, Drexler adopted and translated Feynman's visions in terms of "molecular manufacture", while ignoring Feynman's remarks on the specificities of physics at the nanolevel. Drexler was subsequently caught up in a controversy around these issues with chemists [Smalley 2001], [Whitesides 2001] and physicists [Jones 2004] alike, which discredited him in the eyes of the scientific community. Indeed, most scientists active in the early decades of nanoresearch had never heard of Drexler and his speculative views on molecular manufacturing [Toumey 2005, 2008].

Does this mean that Drexler and Feynman had no impact whatsoever on nanotechnology? One could argue, with a touch of cynicism, that the title of founding father of nanotechnology should be awarded not to Richard Feynman but to Bill Clinton who launched the first, generously-funded National Nanotechnology Initiative at the end of his mandate at the White House. Furthermore, Drexler's prediction that the bottom-up approach would soon consign the conventional top-down methods of chemical manufacture to a bygone era has proven wrong. Thirty years on, lithographic methods are still widely used for fabricating electronic nanodevices, despite significant advances in the bottom-up synthesis of nanomaterials through the self-assembly of molecules. The contemporary world of nano-engineering deploys a broad spectrum of techniques of synthesis ranging from chemical vapour deposition to molecular recognition, but precision top-down design still has a future. Nevertheless, as Chris Toumey argues in this volume, Drexler's claims deeply influenced the popular view of nanotechnology. Drexler's grand futuristic visions also informed the hype around the earliest programs of nanoresearch, calling forth not only a plethora of metaphors such as nanorobots and nanomissiles, which appealed to various audiences, but also a range of extravagant promises that nanoscience would provide the solutions to all our contemporary problems, including depleted resources, pollution, cancer, and epidemic disease [Berube 2006].

2 From prophecies to promises

The first US Nanoinitiative launched in 2000 led to increased on-the-ground engagement in nanoresearch as well as a multiplication of the promises associated with this research. This culminated in the more ambitious program of Converging Technologies for Improving Human Performance, known by its acronym NBIC (Nanotechnology, Biotechnology, Information technology and Cognitive science), as presented in a report from 2003 commissioned by the National Science Foundation [Roco & Bainbridge 2003]. Nanotechnology was clearly meant to be the driving force in the proposed process of convergence. This report held out three major promises. In simple terms, nanotechnology would make people healthier, wealthier, and wiser.

First, the NBIC report announced a disciplinary "renaissance" in science due to the blurring of the boundaries between physics, chemistry, biology, computing and cognitive science at the nanoscale. The characteristic trajectory of modern science towards division into separate, independent disciplines and sub-disciplines would be countered by the cross-fertilization between the different disciplines characteristic of nanoresearch. Second, the rapid progress resulting from this convergence would result in technological advances that would be extremely interesting for industry. Third, from an anthropological perspective, this report clearly announced that the resulting "disruptive" technologies [Bower & Christensen 1995] would enhance human performance both individually and collectively. The report also established a strong connection between nanotechnology and transhumanism, which is not altogether surprising considering that its co-editor, William Bainbridge, was chair of the World Transhumanist Movement.

The association between nanoscience and human enhancement underlined in the original report triggered a lot of public debate, but this aspect disappeared from the ten-year report on NBIC, supporting the idea that it was only initially present because of Bainbridge's influence [Roco 2011]. Nevertheless, along with concerns about the public acceptance of nanotechnology, the transhumanist connection was an important factor behind the recruitment of social scientists onto a number of research programs on nanotechnology. Chris Toumey's reflections on his own participation in this movement suggest that the various programs for anticipating the ethical, legal, and social impact (ELSI) of nanotechnology opened up opportunities for scholars in the humanities. On the model of biotechnology, social science in the nanosciences generated a mini-industry within the humanities with hundreds of publications, a society S.Net (Society for the Studies of New and Emerging Technologies), and a journal *NanoEthics* that provided a forum for discussing the issues raised by technologies that converge at the nanoscale. In the early decades this intensive scholarly production greatly favoured studies concerned with predicting the future as well as speculative ethics focused on human enhancement. But the journal and S-Net conferences also welcomed and continue to publish more concrete studies of regulation based on risk analysis and nanotoxicology, sociotechnical imaginaries and issues around public engagement in science.

The promise of disruptive technologies that could provide a competitive edge continues to attract venture capitalists, entrepreneur-scientists with their own start-ups, as well as larger better established industrial groups, although public money remains the principal source of funding. The federal budget of the US National Nanoinitiative increased from $450 million in 2001 to 2.1 billion in 2011. While it actually decreased to 1.2 billion in 2018, the cumulative total investment has nevertheless topped $25 billion since the inception of the NNI at the beginning of the century. In Europe, the Graphene Flagship initiative launched in 2013 with a €1 billion budget over ten years suggests that nanomaterials retain their attractiveness. Graphene, a one-atom layer of graphite often described as a "pure surface" is presented as a wonder material that will lead to a significant leap forward in electronic devices, energy generation and storage, composite materials, and biomedical applications, among other prospective uses. Constructed around this innovative product, the Graphene Flagship project finances research into 2D materials while supporting partnerships between the scientific research community and private companies in order to leverage the available resources and encourage innovations with a direct impact on the European economy.

From the perspective of scientific disciplines, we have still to see any clear signs of the reorganization of knowledge as a result of the convergence of technologies, notably the NBIC convergence triggered by nanoresearch. While traditional scientific disciplines are not showing signs of weakening, nanoresearch has certainly contributed to the blurring of boundaries between science and technology. It is through the synthesis of objects that researchers expect to better understand the physics of the nanoworld. In this research, knowing and making become fused into a single performance. Researchers are more interested in what atoms, molecules and genes can do, or in what they can do with them, than in what they are in a deeper ontological sense. The building blocks of matter and life are reconfigured as nanomachines and explored for their functionalities rather than as the structural units of matter and life. In his contribution to this journal Alfred Nordmann underlines this shift in epistemic culture from theory to practice, suggesting that the nanosciences work with "closed theories" which they do not seek to elaborate. Thus, the goal of the nanosciences is first and foremost “proof of concept” which, according to industrial lore, represents the first step on the path to commercial applications.

Thanks in large part to the constitution of interdisciplinary teams to conduct nanoresearch around diverse projects, there are now many examples of cross-fertilization between disciplines and the emergence of new domains such as bioinformatics, nanophotonics and spintronics. Still, while research in the areas of nanophotonics, spintronics, and optoelectronics has been pursued under the aegis of nanoresearch projects, these areas are understood as being sub-disciplines of physics.

If anything, nanoresearch seems to have strengthened disciplinary affiliations. While many supramolecular chemists jumped onto the nanotechnology bandwagon in the 2000s they did not leave their chemistry departments, nor did they stop publishing in their specialist disciplinary journals. The effect of nanoresearch has been to open up new sub-disciplines within chemistry such as surface chemistry or biomimetic chemistry rather than to construct a new independent discipline. The 2016 Nobel Prize in Chemistry awarded to James Stoddart, Jean-Pierre Sauvage and Ben Feringa clearly reinforced the chemists’ authority over the nanoworld. In their Nobel lectures both Stoddart and Sauvage insisted that they used only the resources of chemistry—templates and molecular topology in particular—to make the catenanes, rotaxanes, switches, and shuttles that fuelled their research.

The positive reinforcement of traditional disciplines through nanoresearch is even more pronounced in the case of biology. Xavier Guchet’s contribution to this issue clearly demonstrates the gulf between the NBIC discourses and the actual practices of nanomedicine. Nanotechnology has been instrumentalized by biologists to pursue either their own biomedical research as is illustrated by the case of tissue engineering, or their own dreams as can be seen more broadly in the area of synthetic biology. Although the Biobrick program, which has been the driving force for the promotion of synthetic biology, can be viewed as a perfect illustration of the NBIC agenda, combining as it does information technology with molecular biology, and exemplifying the bottom-up approach, from bricks to modules and then to systems, its promoters have chosen to identify their research field as a branch of biology, thus marking their distance from the NBIC program [Bensaude-Vincent 2013]. In examining the practices involved in synthetic biology in this issue, Luis Ujéda shows how the discourse about NBIC distorts and oversimplifies the complex process of interaction between biology, chemistry and computer engineering. We can conclude, therefore, that the NBIC program has triggered a centripetal dynamic in nanoresearch rather than the predicted convergence of disciplines. Furthermore, as many have remarked [Vinck & Hubert 2017], and it is a theme taken up by several authors in the current volume, the contemporary world of nanoresearch in the late 2010s is highly diverse. Today “nano” functions more as a generic marker than as a label for any specific scientific domain.

3 The problematic epistemic status of nanoresearch

Thirty years after the emergence of the field, there is still no agreement as to what constitutes nanotechnology. Indeed, if the domain exists at all, it is defined a minima by the reference to the nanometer scale, which is used, for example, by the National Nanoinitiative and by the ISO. In this "official" literature, nanotechnology is science, engineering, and technology conducted at the nanoscale, which is generally defined as running from 1 to 100 nanometers. This standard definition provides a tenuous basis on which to construct a unified field of research let alone a viable scientific discipline.

There is no consensual definition shared between the various actors involved in the investigation, design, engineering or manufacture of nano-objects either. There are as many definitions as there are teams of nanoresearchers, and probably even more, as not everyone in a single team would agree on a single definition. Thierno Guèye in his contribution to this volume deplores the plurality of definitions which he regards as a symptom of social relativism. He makes a brave attempt to construct an "objective definition" based on the genesis of nano-objects and detached from social actors. However, his epistemological approach leads to a definition of nanos as "all techno-scientific activities aimed at knowing or manufacturing more or less complex objects by means of STMs or similar microscopes". Such a definition is far too restrictive to embrace the range of nano-objects that have come into existence over the past decades. Not all of them are produced using STMs, far from it. The definition is even less adequate to cover the range of research in the field, as many researchers use neither STMs nor AFMs and yet this work is clearly accepted as valid nanoresearch by their colleagues.

A central paradox of contemporary nanoresearch is the diversity that hides behind an apparent unity or at least a proposed coherence born by the terms nanoscience and nanotechnology. Take, for example, a leading journal in the domain: *Nature Nanotechnology.* This is a domain-specific publication of the Nature group launched in 2006. If we look at the four featured research highlights articles from the May 2018 issue, we see a clear illustration of the diversity in the nanosciences. One article is about the two-dimensional structure of perovskites, exploring questions in materials sciences [Bubnova 2018]. A second treats issues of photon transfer for possible applications in nano-based telecommunications [Heinrich 2018]. A third article takes us into the domain of synthetic biology with a treatment of functional cellular material (in this case polymersomes) [Pastore 2018] and the last of the four "highlights" proposes a way to obtain electricity from water using oxygen-modulated carbon nanotubes in combination with untreated nanotubes as electrodes [Sun 2018]. While diversity is doubtless a criterion for selecting these highlight articles, it is clear that the editor had a range to choose from. When we compare these four articles with one another, it is not at all evident how the four subjects could be considered to belong to the same scientific field. And that, in a nutshell, is the glory of contemporary nanotechnology.

The lack of consensus about a definition of nanos and the irreducible diversity of practices covered by this umbrella term are the symptoms of its peculiar epistemological status. By no means can nanoscience be considered a "normal science" in Thomas Kuhn's sense. Take the following description Kuhn gives of normal science at the beginning of his classic book:

> In this essay, "normal science" means research firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice. [Kuhn 1962, 10]

Here, we could follow the path suggested by Thierno Guèye and take STM (and to a lesser extent AFM) as paradigmatic, or the construction of certain nano-materials, maybe nanotubes or graphene, as the scientific achievements in question, which might serve as the foundations for nanoscience. In very abstract terms, this approach may seem to do the job, lending coherence to a dispersed field. But, as we have just suggested, we do not have to look very hard to find projects that are considered nanoresearch but do not rely on these forms of microscopy and do not use these particular nanomaterials. More fundamentally, however, if we consider the examples that Kuhn used himself—Einstein's theory of relativity, Lavoisier's oxygen theory or Copernicus' heliocentric astronomy—we see that our suggestions are not going to give us a science that resembles those Kuhn was thinking about. Even if STM and certain nano-materials were adequate references for unifying the field, what the nanosciences would offer us is not a very good fit in terms of Kuhnian paradigms. Kuhn's choice of examples suggests he is thinking about coherent englobing theories that dictate the scientist's engagement with the world (both theoretical and practical) and it is hard to find any equivalent in the different areas of nanoresearch. There is no consensus on key theoretical assumptions, no universal (or generalizable) exemplars, nor is there really any well-defined, consensual body of practical nanotechnology that could constitute something like a paradigm. Furthermore, nanoscience never became a discipline in the academic sense, despite being several decades old and boasting the typical markers of the establishment of a distinct research field such as specialist journals and annual conferences.

In terms of scientific identity, when people in a nanoresearch team talk about their colleagues, they will refer to the physicist, the biologist, the chemist or the pharmacist in the team, rather than thinking of themselves as all being nanoscientists together. These older, better established disciplines are where the scientists have received their professional training and it is where they look for recognition as well as the rules that guide their professional life and their research. Disciplinary affiliations are remarkably resilient and solidly resist the revolutionary claims of a new transversal field like nanoresearch.

One reason that nanoresearch has not (yet?) established itself as a new transdisciplinary domain is that it seems to be a particular kind of approach that can be applied to different types of objects, “enabling” interdisciplinary research projects. For instance, a physicist like Christian Joachim has taken advantage of the technological possibilities offered by new-generation STMs to further explore the quantum properties of atoms with the vague objective of challenging the foundations of quantum mechanics as proposed by Louis de Broglie. Nanoresearch has also enabled pharmaceutical research to develop targeted drug-delivery techniques in order to improve the therapeutic effect of well-established molecules rather than searching for new wonder miracle molecules. Hence the importance and the success of the military metaphors used to convey the view of increased precision and control rather than a new “arsenal” of drugs (see the contribution by Gry Oftedal to the present issue). More globally, the nano approach broadens the field of potentialities and enhances our actionability on molecules. Nanoresearch has certainly encouraged interdisciplinarity but failed to generate the expected transdisciplinarity through the convergence of disciplines. Significantly, the 2018 NSF budget of the US National Nanotechnology Initiative is still distributed among the different disciplines such as the biological sciences, computer and information sciences and technology, engineering, the geosciences, the mathematical and physical sciences [NNI 018]. In other words, traditional disciplines have resisted the NBIC offensive remarkably well.

4 A paradigmatic technoscience

If nanotechnology does not fit the Kuhnian paradigm-based model of normal science, it may be because it belongs to a new regime of knowledge production. Following other philosophers, we characterize this regime as technoscience, a term referring primarily to the merging of science and technology, not only in the sense of application-oriented research, but also in the sense that technology drives research projects, as STM has done in the emergence of nanoresearch.[2] Nonetheless, nanoresearch is much more than technology-oriented or instrument-driven research. It is above all a painstaking laboratory practice of design of tiny, invisible, unfamiliar objects. Such molecular materials and machines are made neither as potential candidates for technological breakthroughs, nor as samples of physical or biological phenomena used to test theoretical hypotheses. These material realisations are interesting in their own right, and they serve as tools for exploring a new world of surprising and often unpredicted possibilities and opportunities.

2. This reciprocal internalization of science into technology and technology into science is what Gilbert Hottois had in mind when he coined the term technoscience [Hottois 1984].

In his assessment of the impact of nanoresearch on the philosophy of science, Alfred Nordmann emphasizes how it has elicited new responses to familiar epistemological issues such as the respective roles of theory and experiment or observation. However, his epistemological analysis of nanoresearch practices strongly suggests that nanoresearch is also raising new philosophical and ethical issues. For instance, the fact that nano-objects such as carbon nanotubes are constituted through the contingent circumstances of their particular histories raises difficult questions for risk assessment, and at the same time, brings about a new relationship between human subjects and the objects they produce. Nano-objects are so individualized by their genesis and their interactions with their environment that they cannot be treated as representatives of a class of natural phenomena. They are just made to work, individually, project by project, meaning that nanoscientists are often content with publishing "proofs of concept". In this context, demonstrating the existence and the performance of a nanoresearch object is more important than establishing overarching natural laws. Nanoresearch thus subverts the hierarchy of epistemic values in science. Certain forms of nanoresearch look like a quest for exceptional performance in extreme conditions, like a spectacular sports race or the attempt to establish a new world record. Sacha Loeve's contribution to this issue presents the International NanoCar Race as an example of the "gamification" of nanoresearch through an international competition. But although this race is presented as a game, it is a serious game. The race was set up with the purpose of defining standards for nanocars through a comparison of their behaviour in the same experimental setting.

5 Enduring ethical challenges

Faced with a proliferating and ramifying domain of nanoresearch that conforms to the classical canons of neither theoretical science nor technological innovation, we need to think carefully about the ethical issues raised by this domain of technoscience. Up until now, a significant proportion of the philosophical literature about the ethics of nanoresearch has been oriented towards the transhumanist potential of a convergence between biological engineering and nanoresearch. Nevertheless, as such applications of nanoresearch still seem a long way off, the ethical discussions around them remain rather speculative [Nordmann 2007].

On the other hand, researchers, policy makers, industrial managers, and civil activists are very concerned about the potential toxic effects of nanomaterials, and these issues will become all the more pressing as nanomaterials proliferate and find their way into greater numbers of everyday items. Such application-related issues have attracted most of the attention in the framework of ELSI programs. Thus, what we might term the practical or technical ethical engagement has focused on the identification of risks (mostly health risks) and attempts to evaluate or to quantify them. Nevertheless, when identified, such as the discussion around the potential pulmonary toxicity of carbon nanotubes, the potential health and environmental risks have so far been largely outweighed by the projected benefits expected from future applications of the materials in question.

To conclude this introduction, we would like to raise the much broader question of how to engage with the ethical questions raised by today's nanoresearch. As we have just suggested, the current norm consists in anticipating and preventing the adverse effects of innovation in nanoresearch, particularly concerning the environmental effects of new nanoparticles. But this work remains in the mode of a managerial approach: risk assessment, prospective studies and preventive measures. Although undoubtedly wise, this kind of prospective preventive approach does not exhaust the range of ethical issues in a domain like nanoresearch, and it is time to start thinking more broadly about the subject. Let us start from the principle that we will adopt a consequentialist position and judge the rightness of our actions based on their consequences (rather than on the intentions of an agent or the inherent "goodness" of the action). This seems to be the position behind programmes of Responsible Research and Innovation (such as the one funded by the European Union—`https://ec.europa.eu/programmes/horizon2020/`). The problem here is that the range of consequences taken into account remains too limited and we find ourselves restricted to the domain of the technical fix for what is conceived of as a technical problem. If we are to develop an adequate analysis, we need to open up the scenarios and range of relevant actors much wider. Here, we can learn from the history of other synthetic materials, such as ethylene-based polymers, where the use and subsequent dissemination of the material has been far in excess of what was necessary or reasonable at the time of their introduction, leading to the ubiquitous presence of microparticles of these plastics across the globe. The distribution and use of these synthetic polymers is the consequence of a whole range of factors, notably industrial and political policies, but also trajectories of individual use that have depended as much on the ready availability of the material as on its adaptation to unforeseen uses. The risk with novel nanomaterials is to remain in the mode of a technical fix for a well-identified problem rather than to conceive the introduction of these new materials into a world where industrial and political policies are the principal determinants of use. Thus, to be prepared for the new world of nanos, we need to open up the field instead of limiting it to the classically conceived issue of risk. In this context, it is important to address a distinctive feature of nanoresearch which is picked up in a number of papers in this issue: the weaving together of commercial and economic goals with cognitive aims. These traditionally distinct goals have become so tightly bound up together in nanoresearch that it is difficult to tease them apart. The claims of economic competitiveness or national prestige that are put forward to legitimize the different national or regional nanoinitiatives are more than just rhetorical discourses. They impact the research practices and the design of nano-objects. Thus, these tiny objects come into being at the intersection of heterogeneous systems of values: epistemic values (proof of concept), technological values (control, efficiency), environmental and health values, as well as political and economic values. As they bring together these potentially conflicting systems of values they challenge ethical and political categories, obliging philosophers to reconsider how democratic societies can handle such densely value-laden objects. In the face of the variety of actors involved, and the diversity of scientific, industrial, and geopolitical interests at stake, nanoresearch requires a continuous dose of reflexivity concerning both its fundamental research and its commercial applications.

Bibliography

Bensaude-Vincent, Bernadette [2013], Discipline-building in synthetic biology, *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences*, 44(2), 122–129, doi: 10.1016/j.shpsc.2013.03.007.

Berube, David M. [2006], *Nano-Hype. The Truth behind the Nanotechnology Buzz*, Amherst; New York: Prometheus Books.

Bower, Joseph. L. & Christensen, Clayton M. [1995], Disruptive technologies: Catching the wave, *Harvard Business Review*, 73(1), 43–53.

Bubnova, Olga [2018], Stand up to stand out, *Nature Nanotechnology*, 13(5), 356–356, doi: 10.1038/s41565-018-0151-x.

Drexler, K. Eric [1986], *Engines of Creation. The Coming Era of Nanotechnology*, New York: Anchor Books, trad. fr. par M. Macé, révisée par Th. Hoquet, *Engins de création : l'avènement des nanotechnologies*, Paris: Vuibert, 2005.

—— [2004], Nanotechnology: From Feynman to Funding, *Bulletin of Science, Technology & Society*, 24(1), 21–27, doi: 10.1177/0270467604263113.

Feynman, Richard P. [1959], There's plenty of room at the bottom, in: *Miniaturization*, edited by H. D. Gilbert, New York: Rheinhold Publishing Co, 282–296, `http://www.zyvex.com/nanotech/feynman.html`.

Heinrich, Benjamin [2018], Telecom single photons thaw, *Nature Nanotechnology*, 13(5), 356, doi: 10.1038/s41565-018-0152-9.

Hottois, Gilbert [1984], *Le Signe et la Technique. La philosophie à l'épreuve des techniques*, Paris: Aubier.

Jones, Richard [2004], *Soft Machines*, Oxford; New-York: Oxford University Press.

Kuhn, Thomas [1962], *The Structure of Scientific Revolutions*, Chicago: University of Chicago Press, 4th edn., 2012.

Mody, Cyrus [2004*a*], How probe microscopists became nanotechnologists, in: *Discovering the Nanoscale*, edited by D. Baird, A. Nordmann, & J. Schummer, Amsterdam: IOS Press, 119–133.

—— [2004*b*], Small, but determined: Technological determinism in nanoscience, *Hyle – International Journal for Philosophy of Chemistry*, 10(2), 99–128.

Nordmann, Alfred [2007], If and then: A critique of speculative nanoethics, *NanoEthics*, 1(1), 31–46, doi: 10.1007/s11569-007-0007-6.

Pastore, Chiara [2018], Sensing cellular cues, *Nature Nanotechnology*, 13(5), 356–356, doi: 10.1038/s41565-018-0153-8.

Roco, Mihail C. [2011], The long view of nanotechnology development: the National Nanotechnology Initiative at 10 years, *Journal of Nanoparticle Research*, 13(2), 427–445, doi: 10.1007/s11051-010-0192-z.

Roco, Mihail C. & Bainbridge, William Sims (eds.) [2003], *Converging Technologies for Improving Human Performance. Nanotechnology, Biotechnology, Information Technology and Cognitive Science*, Dordrecht: Springer, doi: 10.1007/978-94-017-0359-8.

Smalley, Richard [2001], Of chemistry, love and nanobots, *Scientific American*, September, 76–77.

Sun, Wenjie [2018], Energy from quiescent water, *Nature Nanotechnology*, 13(5), 356–356, doi: 10.1038/s41565-018-0154-7.

Toumey, Chris [2008], Reading Feynman into nanotechnology. A text for a new science, *Techné: Research in Philosophy and Technology*, 12(3), 133–168, doi: 10.5840/techne20081231.

Toumey, Christopher P. [2005], Apostolic succession: Does nanotechnology descend from richard feynman's 1959 talk?„ *Engineering & Science*, 68(1), 16–23, `http://resolver.caltech.edu/CaltechES:68.1.Succession`.

Vinck, Dominique & Hubert, Matthieu [2017], *Les Nanotechnologies : l'invisible révolution*, Paris: Le Cavalier Bleu.

Whitesides, George M. [2001], The once and future nanomachines', *Scientific American*, September, 78–83.